

The William H. Natcher Cable-Stayed Bridge at Owensboro, Kentucky

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ABSTRACT

To compete effectively with an economically designed concrete alternate bridge crossing of the Ohio River required an innovative steel alternate cable-stayed bridge. Just such a structure is nearing completion. The river at the project site is approximately 6.4 kilometers wide between the states of Kentucky and Indiana. Most of the area is a floodplain, which gets inundated at least once a year. As a result, the main bridge, which is 1,375 meters long, requires a long approach on the Kentucky side. This approach consists of embankments and relief structures to allow for the passage of flood waters. This paper discusses the many noteworthy aspects of the William Natcher Bridge.

KEY WORDS: Cable-Stayed Bridge; Floodplain; Hydraulic Studies; Scour; Towers; FESWMS Model; Edge Girder; Floor Beam; Overlay; Stay Cables; Connection; Wind Tunnel Testing; Vortex Excitation; Flutter; Construction; Counterweights

INTRODUCTION

The William H. Natcher Bridge, which is nearly complete, will carry U.S. Route 231 over the Ohio River between Owensboro, Kentucky and Rockport, Indiana. Parsons Brinckerhoff designed this 366-meter main span steel cable-stayed bridge (Figure 1) for the Kentucky Transportation Cabinet.

Since the William Natcher Bridge is the longest cable-stayed span over the U.S. inland waterway system, its design required careful evaluation to achieve an efficient, safe and durable bridge. An innovative design resulted in a bridge that is “user-friendly,” not only during construction, but also for inspectors and maintenance personnel once the bridge is completed. Some of the bridge’s noteworthy features include:

- Simple and flexible details of the stay cable to girder anchoring system
- Efficient prefabricated composite steel stay cable anchoring system in the towers
- Continuity of the superstructure at the anchor piers with the approach girders
- Concrete counterweight instead of conventional tiedowns at anchor piers

BRIDGE CONFIGURATION

The Ohio River Valley at the project site is approximately 6.4 kilometers wide between the states of Kentucky and Indiana. Most of the area is floodplain, which gets inundated at least once a year. On the Kentucky side, it was necessary to incorporate a long approach consisting of embankments and relief structures to allow for the passage of flood waters. The main river crossing from abutment to abutment is 1,375 meters. It provides a 335-meter-wide shipping channel and accommodates a vertical clearance of 24 meters above the normal pool elevation of 110 meters (Table 1 and Figure 2).

DESIGN CRITERIA

The bridge was designed in accordance with American Association of State Highway and Transportation Officials (AASHTO) Specifications. The following design criteria were used:

- AASHTO HS-20 truck load increased by 25%
- Barge impact forces over the length of the total bridge, specifically:
 - Land approach: single 180-ton empty jumbo barge moving with the current at 100-year-flood condition
 - Water approach and main crossing: 15 (3 x 5) fully loaded jumbo barges with tow moving under power with the normal current or single 1,700-ton jumbo barge moving with the current at 100-year-flood condition (maximum force = 13,300 to 17,800 kN)
- Seismic force per AASHTO Seismic Performance Category B (0.10 g)
- Restricted channel closing to barge traffic
- 100-year return wind speed = 130 kph
- Scour plus barge impact = 50% scour depth for normal flow and 100% scour depth for 100-year-flood flow
- Gravity, thermal and transient loads
- Stay cable replacement with only the two farthest lanes fully live loaded
- Accidental loss of a cable with all lanes fully loaded

HYDRAULIC ANALYSIS

A state-of-the-art hydraulic analysis and scour evaluation was performed of the 6.4-kilometer-wide Ohio River floodplain in the area of the Natcher Bridge. This evaluation included the main river crossing and the relief structures in the overbank areas on the Kentucky floodplain side. Of particular concern was the effect of the bridge on the flow characteristics of the river. The objective was to determine the optimum arrangement of the Kentucky approach relief structures, whereby fast-flow conditions are avoided and scouring of the soil around the bridge foundations is minimized.

Using the Finite Element Surface Water Modeling System (FESWMS), a finite element model of 89 square kilometers of floodplain in the vicinity of the crossing was created and analyzed. The hydraulic analysis provided flow and discharge vectors at every nodal point in the model. The flow velocities were then used to calculate the severity of anticipated scour and the depth needed for the bridge foundations.

More than 14 alternatives were studied, each with 8 to 10 options. Only two adequately met the design objectives that flow rate not exceed 1.22 meters/second immediately downstream of the bridge and that backwater elevation not exceed 76 millimeters. After a detailed comparative evaluation was performed that examined cost, hydraulics, operations and maintenance, the Kentucky Transportation Cabinet selected the alternative with five flood relief structures in the overbank area on the Kentucky side. Utilizing information provided by the FESWMS model and the Federal Highway Manual on scour (HEC18), contraction scour and general scour were computed at each main bridge pier and at the flood relief structures. The computed scours were incorporated into the foundation design and the velocity vectors were used in determining ship impact forces.

TOWERS

The Natcher Bridge has two identical concrete towers supporting three main superstructure spans through the stay cables. The towers are 100.6 meters high, rising 79.3 meters above the bridge deck. The towers are the most dominant elements of a cable-stayed bridge and the importance of their shape cannot be overemphasized. After a comprehensive evaluation of tower shapes during preliminary design, a diamond-shaped tower was selected (Figure 3). This shape results in improved torsional stiffness of the superstructure and stability of the bridge during construction and against seismic and wind loads when the bridge is in service.

Above the deck level, each tower has two hollow inclined legs that meet at the top to form a large trapezoid-shaped chamber in which the stressing ends of the cables are anchored. The chamber is outfitted with ladders and working platforms to facilitate inspection and maintenance. This is one of the few bridges where the cable anchors can be easily and directly accessed.

Below the deck, the tower legs bend inward and are held in position with a post-tensioned concrete tie beam. At each tower, the superstructure passes through the upper legs and sits atop the tie beam with bearings under each edge girder. Bearings at the Kentucky tower are fixed, while those at the Indiana tower allow for expansion.

CABLE-STAYED SUPERSTRUCTURE

The cable-stayed superstructure consists of steel I-shaped edge girders and floor beams made composite with the concrete deck slab using shear studs (Figures 4 and 5). The edge girder web is inclined at 8° to match the inclination of stay cables, and the floorbeams are spaced at 4.6 meters. The deck slab consists of 230-millimeter-thick precast concrete slab panels with cast-in-place infills. To control torsion in the floorbeams during precast slab erection, a central beam is provided. A 38-millimeter latex modified concrete overlay will be placed on the deck slab.

SUPERSTRUCTURE CONTINUITY AT ANCHOR PIERS

The cable-stayed superstructure is continuous with the steel stringer approach spans, three spans on the Kentucky side and a single span on the Indiana side. The transition from the cable-stayed back spans to the adjacent approach spans at the anchor piers is an innovative feature of the William Natcher Bridge that offers several advantages:

- The dead load reaction from the approach spans reduces counterweight requirements
- Expansion joints are avoided, thereby eliminating the potential for leakage of water onto the bearings, tie downs and windlocks
- There is no relative translation or rotation between the two adjacent spans, providing a smoother ride

In the transition area, six longitudinal approach stringers are framed into the two cable-stayed edge girders through a series of three floor beams (Figure 6). Moments are transferred by upward and downward forces on these floor beams. The approach stringers, edge girders and floor beams are all 3.7 meters deep at this location, beyond which the two cable-stayed edge girders gradually decrease to a typical depth of 1.5 meters.

COUNTERWEIGHTS

The counterweights are integrated into the superstructure and placed so that their centers of gravity coincide with the centerline of bearing at the anchor pier. The counterweights completely balance the uplift, even for the worst loading case with a full live load exclusively on the main span. To increase the factor of safety against uplift to two, as required by AASHTO, the anchor piers are also provided with tie-downs designed to resist the maximum upward live load reaction without the counterweights. These tie downs act as a back up and will never become tensioned unless there is an extreme situation. Because the tie downs will generally not be under tension, they can easily be maintained periodically. Often only tie downs are utilized to resist uplift in cable-stayed bridges; however, maintenance of these “active” tie downs is costly and difficult.

LONGITUDINAL FIXITY

The total length between expansion joints of the cable-stayed spans and the steel stringer approach spans is 1,030 meters. Longitudinal fixity is provided at the Kentucky tower only (Figure 7). Here two brackets drop down from the edge girder and hug a heavily reinforced concrete pedestal. Steel reinforced elastomeric bearing pads that rest between the steel brackets and the pedestal transfer the longitudinal force. Each pad has a PTFE surface that bears against the bracket so that rotation of the girder is not hampered.

STAY CABLES

The bridge has a total of 96 stay cables made of 15-millimeter-diameter seven-wire strands, with cross ties provided to control galloping. To maximize economy, the specifications gave the contractor the option of using either greased and sheathed strands or epoxy-coated strands, grouted in either a black high-density polyethylene (PE) pipe wrapped with white tedlar tape or coextruded PE pipe with a white exterior. The contractor was allowed further flexibility in selecting the anchor type for the cable anchorage assemblies, which were designed to accommodate wedge, wedge socket and socket type cable anchors. The contractor elected to use greased and sheathed strands grouted in coextruded pipe, and wedge type cable anchors, all supplied by VSL Corporation. The pipe is provided with a spiral bead to control rain/wind-induced vibrations.

CABLE-TO-GIRDER CONNECTION (NON-STRESSING END)

The cables are connected to the girders by means of a simple bolted splice between the cable connection assembly and girder web (Figure 8). This eliminates torsion in the edge girder, allowing the connection to be located between floor beams. To provide for shear flow in the edge girder where the top flange has been slotted, angles are bolted to the connection plate and to the top flange, along the slot. The connection plate is a flat steel plate that passes through a slot in the top flange of the edge girder as an extension of the edge girder web. A bolted splice connection is chosen to avoid stress concentration and cracking of weldments. The other end of the plate is cut into a tuning fork shape with two prongs, between which a thick-walled pipe is welded. A shim plate supports the anchor head to bear against the end of the pipe.

Two additional plates are welded to the connection plate and the pipe to stiffen the pipe against squashing and reduce the required thickness of the connection plate. These plates give the cross section of the connection a cruciform shape. They are tapered and stop above the top of the cast-in-place portion of the concrete deck, which is poured around the connection plate. The cruciform shape is an open section that allows easy access for inspection. Below the edge girder top flange, the splice connection can also be easily inspected.

The cable anchorage is located above the deck, which makes it easy for construction workers, inspectors and maintenance personnel to access the cable anchors directly without need for expensive special equipment.

CABLE-TO-TOWER CONNECTION (STRESSING END)

The cable-to-tower connection consists of steel frames anchored to the interior walls of the tower head chamber by shear studs. These frames carry the horizontal component of the cable force and transfer the vertical component to the concrete (Figures 9 and 10). They can also transfer unbalanced cable forces during cable replacement or loss.

Each tower head contains 12 steel frames, each supporting two side span cables and two main span cables. A frame consists of two built-up channels with flanges inclined to match the slope of the inner tower walls. A cap plate with a steel pipe is welded to each end of the channels, and the inclined flange and cap plates are attached to the tower walls with shear studs. The cable bears against inclined support plates that are sandwiched between the channel flanges.

This was the first bridge in the U.S. where a composite anchorage using steel frames for a cable-stayed bridge has been implemented. The design has proved to be economical, easy to construct, and provides satisfactory geometry control.

The closed chamber at the top of the tower piers provides a protected environment for the cable anchorage and is a convenient location for cable stressing operations. Platforms located at each cable level provide direct access to the frames and anchorages for inspection and maintenance.

WIND TUNNEL TESTING

To ensure aerodynamic stability, a wind study was performed for the bridge that included wind data collection and analysis and wind tunnel tests. Rowen Williams Davies and Irwin, Inc. (RWDI) was retained to perform the wind study. Wind tunnel tests were performed on both sectional and a full aeroelastic model. An aeroelastic model was used to test the bridge during four construction stages, as well as when completed. The results confirmed the adequacy of the design. The various criteria used for testing the William Natcher Bridge encompassed:

- Design wind speed of 132 kph to compute static wind loads
- Minimum flutter speed of 154 kph to study the dynamic wind effect
- Structural peak acceleration limits of 5% of gravity up to 48 kph and 10% of gravity above 48 kph for studying vortex excitation

All models were tested for smooth and turbulent air flows. The vortex excitation was within the criteria and occurred around 72 kph. Flutter speed was around 192 kph, well above the 154 kph predicted every 100,000 years at the site.

AESTHETICS

Consideration of aesthetics is essential for bridges of the size and stature of the William Natcher Bridge. During the design process, Parsons Brinckerhoff's in-house architects were consulted on the aesthetics of the various bridge elements. All elements were initially defined considering the functional objectives and then reviewed by the architects, who recommended several aesthetic enhancements. For instance, the shape of the towers was selected based on economy, functionality, constructibility, inspectibility, maintainability, torsional deck stability, cable connectivity, etc. However, once the initial shape was chosen, the architects gave the towers' sides a slight taper and sculpted the exposed faces at the tower tops, giving them definition in the form of relief and striation. Attention to aesthetics along with functionality resulted in a bridge that is beautiful and graceful without sacrificing the design objectives.

CONSTRUCTION SEQUENCE

Because controlling load cases for the design of cable-stayed bridges often occur during construction, designing a bridge for anticipated construction stages is as important as designing the completed structure. The cable-stayed spans were designed to be constructed using the balanced cantilever segmental method. This method was selected because it satisfies the requirement that shipping lanes remain free of temporary construction supports. The construction sequence for the balanced cantilever method involves the following steps:

- The tower is constructed.
- The first superstructure segment is erected at the tower and supported by temporary bracing.
- The remaining superstructure segments are erected and cables are installed sequentially on alternate sides of the tower until connections are made at the anchor pier and, finally, at mid span.

Additionally, each superstructure segment is erected in the stages listed below:

- A steel frame is lifted into position by a barge-mounted crane and field spliced to the edge girder of the previously installed segment. It is allowed to cantilever freely.
- Two stay cables connecting the steel frame to the tower are installed and tensioned to an initial length.

- The six precast deck panels are installed and cast-in-place concrete closure strips are placed between them and along the edge girders of the previously installed segment.
- The two cables are tensioned to their final length.

Two-level tensioning of the cables is required to control both erection and “locked-in” stresses in the deck and edge girders. Also, to reduce bending moments in the tower caused by wind loads and construction sequence imbalances, a temporary tie-down is connected to the superstructure of the back span (Figure 11). The temporary tie down is a frame that resists downward force as well. In addition, weights are strategically positioned and repositioned on the deck to control stresses in the superstructure.

CONSTRUCTION STAGE

Construction of the bridge has proceeded smoothly and is essentially complete. The center span cantilevers have been joined, and barrier and overlay placement is ongoing. Figures 12, 13 and 14 show various bridge elements during fabrication or installation.

CONCLUSION

Hands-on inspection and future maintenance are crucial for bridge longevity; however, the cable anchors of cable-stayed bridges are traditionally very difficult to access and critical tie-down devices are often located directly beneath potentially leaking expansion joints. Accessibility and maintainability of these areas were among the most important factors addressed during the design of the William Natcher Bridge. Innovative ideas for cable-to-tower and cable-to-deck connections, as well as for the elimination of uplift bearings and deck joints were developed. The design allows inspectors and maintenance crews to perform hands-on work by walking directly to the cable anchors without using any special equipment. In addition, expansion joints are eliminated at the anchor piers and uplift is resisted by counterweights instead of tie downs. These innovations will result in the first user-friendly cable-stayed bridge in the U.S. (Figure 15). Because design documents were well prepared, only a few inquiries have occurred during construction.

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CREDITS

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Special Advisor:	Schlaich Bergermann and Partner
Stay Cables:	VSL Structural
QA and Advice:	American Institute of Steel Construction National Steel Bridge Alliance Contractors, Fabricators and Erectors

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TABLE 1 Detailed Characteristics of the William Natcher Bridge

Location	Configuration	Superstructure	Substructure	Foundation
Kentucky Approach	Four equal continuous spans for a total length of 134.8 m	Precast, prestressed concrete girders continuous for live load and superimposed dead load with CIP deck	Three-column bents over land	Drilled shafts of 1.2 to 1.8 m diameter, up to 40 m deep
	Three continuous spans of 84-108-84 m	Multiple steel I-girders with CIP deck	Hammerhead piers in water	Drilled shafts of 2.4 m diameter
Cable-Stayed Spans	Three continuous spans of 152-366-152 m	Steel I edge-girders, floor beams, precast deck slabs with CIP concrete infills, 38 mm latex modified concrete overlay	Diamond-shaped towers	Drilled shafts of 1.8 m diameter, up to 25 m deep
Indiana Approach	One span of 84 m	Multiple steel I-girders with CIP concrete deck	Hammerhead pier in water	Drilled shafts of 1.5 m diameter, up to 34 m deep
	Five equal continuous spans for a total length of 209.5 m	Precast, prestressed concrete I-girders continuous for live load and superimposed dead load with CIP concrete deck	Three-column bents over land	Drilled shafts of 1.2 to 1.8 m diameter, up to 34 m deep



FIGURE 1 Computer simulation of the soon-to-be completed William Natcher Bridge.

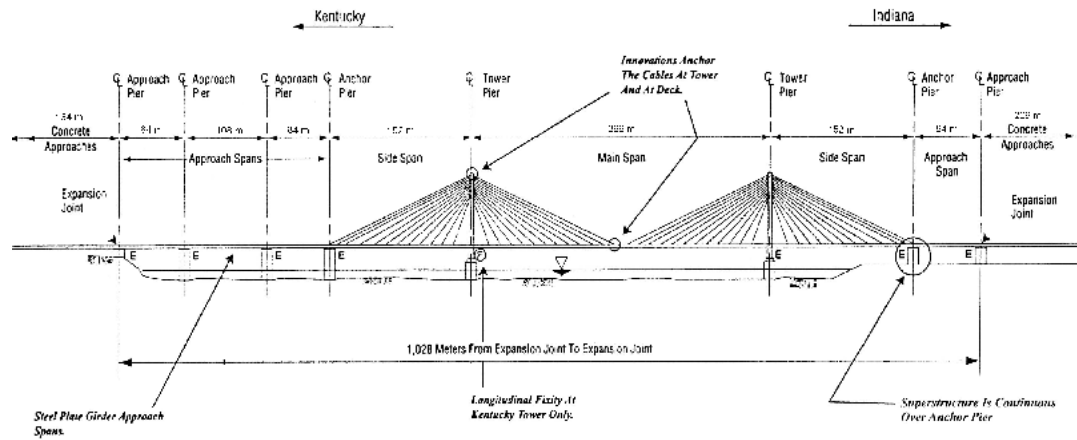


FIGURE 2 Elevation view of the Natcher Bridge.



FIGURE 3 Indiana tower complete. Kentucky tower under construction.

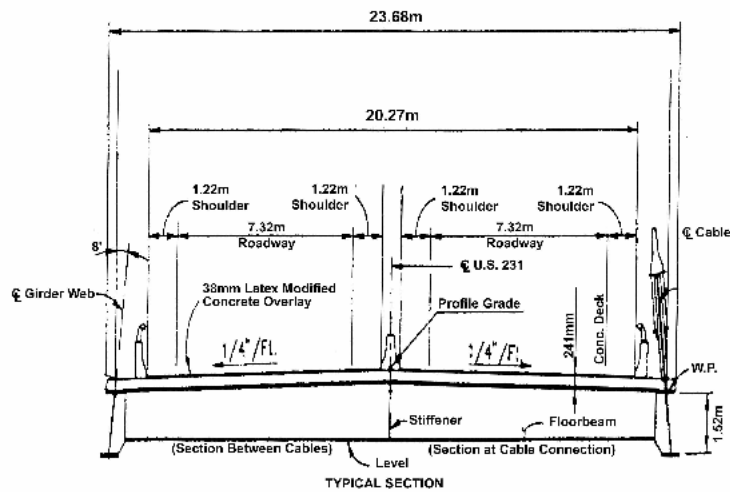


FIGURE 4 Typical cross section.



FIGURE 5 Superstructure being erected.



FIGURE 6 Approach girders, two tapered edge girders and floor beams erected.



FIGURE 7 Bearing at top supports gravity load and vertical bumpers resist longitudinal load.



FIGURE 8 Cable-to-girder connection being installed.

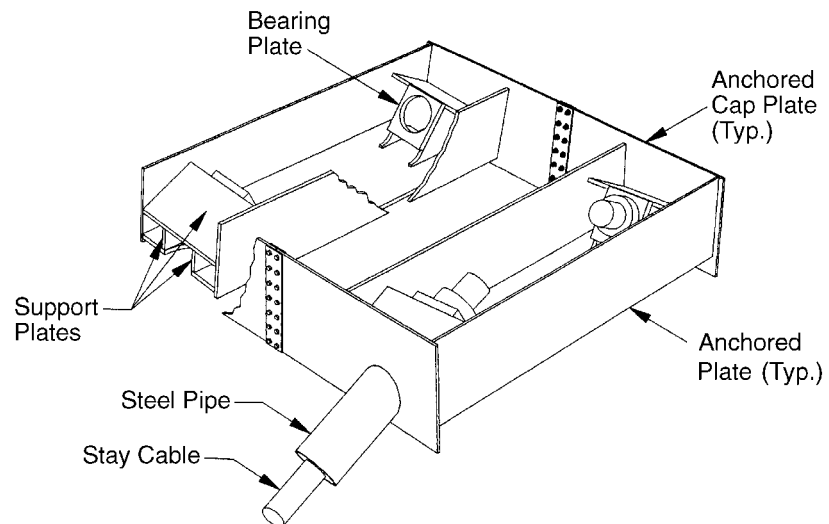
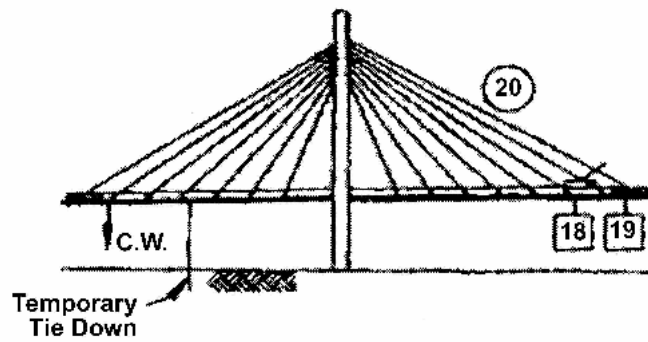


FIGURE 9 Cable-to-tower connection.



FIGURE 10 Inside tower pier top showing easy access to cable anchorage.



- A. ERECT SEGMENT 19 STEEL FRAME
- B. INSTALL CABLES 20 & 20' AND JACK TO INITIAL LENGTH
- C. APPLY 710 kN COUNTERWEIGHT
- D. INSTALL PCC DECK PANELS ON SEGMENT 19
- E. PLACE PHASE 1 CONCRETE ON SEGMENT 19 AND PHASE 2 CONCRETE ON SEGMENT 18
- F. JACK CABLES 20 & 20' TO FINAL LENGTH

FIGURE 11 Typical construction stage.



FIGURE 12 River piers—drilled shaft construction.



FIGURE 13 Starting superstructure erection.



FIGURE 14 Bridge under construction.



FIGURE 15 Main span completed.